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The Moon Is Not Space

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ABSTRACT

The Moon as a venue for remote sensing has certain geometrically-based advantages over free flyers that facilitate reuse of assets: lack of dispersion of emplaced facilities; reduction (compare.d to space) of the dimension of mobility space from 3 to 2; repetitive lunar-station to Earth station communications geometry. If a series of lunar missions is designed so as to build each upon the other-a series of partially reusable hardware assets- there is a point in time when the total cost of lunar-based missions becomes less than an equivalent set of independent free flyers. The economics of reusability is examined along with feasibility (survivability on the Moon over time and methods of connecting successor to predecessor assets). Surveyor 3 (some of whose parts were returned by the Apollo 12 astronauts) *is* used as an anecdotal analysis of survivability along with notes of a more general nature. Some scientific candidates for low-cost remote sensing from the Moon are also presented.

INTRODUCTION

Stretching back into prehistory, the Moon has excited a fascination for humans. This attitude is not exclusive to the domains of mythology and poetry, but, also, the Moon is known to psychologists to influence, to some extent, human actions. After the enormous engineering, scientific and political successes of the Apollo missions to the Moon, that body acquired a second psychological set of associations. Thus, returning to the Moon has often been treated as axiomatically a good thing to do because it serves as a dual symbol.

But for the last decade or so, a more cerebral case for returning, to the Moon has been evolving. The case, depending on who is presenting it, is based upon one or more scientific or economic advantages. Among the (nonmilitary') items listed for rationale are:

(1) The study of the Moon *per se*, e.g., lunar geology

(2) Commercial advantage, e.g., entertainment or power generation.

(3) A base for remote sensing.

This paper is only concerned with item 3: not with peripheral symbolic notions nor with items 1 or 2. (However item 2 does enter in to a limited extent when a "mixed strategy" is discussed, and lunar geology has some environmental consequences for lunar observatories.)

Remote-sensing applications of a lunar venue are obviously attractive for astrophysical investigations, but, less obviously terrestrial observations might be of value, synoptic observations of the magnetosphere for example. A considerable body of work has been done, and published, with regard to the scientific objectives and some elements of design for lunar emplacements, particularly for astrophysics.

The objective of the present paper *is* to sketch some ideas that hold promise. for utilizing the Moon's unique advantages as *a remote-sensing platform* The tests of the potential value of a proposed lunar scientific outpost are twofold: (1) is the "science per dollar" estimate attractive?, and (2) is the Moon preferable to other venues, particularly free flyers? A constraint for all of the investigations is not only high science-per-dollar but also low absolute cost Although "low" is not going to be rigorously quantified here, something in the neighborhood of NASA's Discovery class is envisaged. Therefore, the. observatories are robotic and without human presence.

An attempt to answer, in part, the two questions above has determined the structure of the present paper,

Question (1) is addressed by reviewing some candidate investigations that hold promise of delivering valuable science at low cost The Lunar Observatory Steering Group (LOSG) was established in 1994 by NASA's Mission From Planet Earth Study Office (Code SX) in the. Office of Space. Science (Code S) to examine scientific options. Although the LOSG, an inter-center group chaired by the present author, developed some new scientific and mission options, it largely functioned as a low pass filter to review the excellent sets of scientific proposals in the literature and highlight those which seem to be at the low end of the cost spectrum. Neither the LOSG effort nor the new material presented here should be considered to be complete in any sense. The search for good scientific ideas and clever designs for lunar observatories must be an ongoing process.

Question (2) really reflects the thrust of the paper with regard to what is substantively new, here, as distinguished from the LOSG report[1,2], which placed most emphasis upon question (1). The thesis of this paper is that the differentiator between the Moon and space is that the Moon provides a convenient way to collect scientific. and engineering assets over a period Of time: in a sense, the Moon has a memory.

But, in order for these collected assets to be of use, two conditions must be fulfilled: (1) they must survive in time through the rigors (especially radiation and monthly thermal cycling) of the lunar environment, and (2) there must be a way to connect the assets of one investigation to those of a subsequent one (or even contemporary one). The primary topics of the paper, then, are survivability and connectivity.

An example of an asset that might be reused is a Moon-Earth telecommunications system. in order to effect such reuse, in addition to surviving, the system would have to be controllable by the subsequent investigation (this implies, also, a functioning power source on the original vehicle) and a means to transfer data between successor and predecessor. The last point, connectivity, might be, for example, by a UHF link.

The plan of the paper is to enter into the topics treated above in enough detail to allow judgments to be formed as to whether the trail is worth following in future. The final section collects some possibilities for those who do go down this trail,

LOW-COST SCIENCE FROM THE MOON

As mentioned above, a considerable amount of effort has been expended in the last decade to identify candidate scientific (rc.mote sensing) investigations for implementation on the Moon. The LOSG established a preliminary list of some that might bc expected to be done for a relatively low cost. These investigation concepts arc sketched below. Much more material exists in the literature.[3,4]

Astrophysical Low-Frequency Array (ALFA)

Scientific Objectives

The frequency range below about 30 MHz is unexplored with high angular resolution duc to the opacity of the Earth's ionosphere. An interferometer array in space providing sub-degree angular resolution images would allow a wide range of problems in solar, planetary, galactic, and extragalactic astronomy to bc attacked.[4] These include the evolution of solar and planetary radio bursts (including auroral kilometric radiation (AKR) from the Earth), scintillation caused by turbulence in the interplanetary and interstellar media, the distribution of diffuse ionized hydrogen in our galaxy, the determination of spectral turnover frequencies and magnetic field strengths in galactic and extra-galactic radio sources, statistical tests of radio source unification theories at frequencies where radiation is expected to bc completely isotropic, searches for 'fossil' radio galaxies which are no longer detectable at higher frequencies, and searches for ncw sources of coherent radio emission. In addition, it is likely that completely unexpected objects and emission processes will bc discovered by such an instrument, as has often happened when high resolution astronomical observations first became possible in a wide new region of the electromagnetic spectrum. The low frequency window from about 30 kHz to 30 MHz spans three orders of magnitude in frequency, wider than the infrared window opened by IRAS and ISO or the ultraviolet window opened by IUE and EUVE. It represents the last region of the spectrum which is inaccessible from Earth and still largely unexplored.

Instrument and Mission

Some 15 to 20 identical small packages would be deployed on the lunar mar side surface in a region about 100 km in diameter. Each package would consist of a spherical capsule containing electronics and lithium batteries and a pair of orthogonal wire dipole antennas lying on the lunar surface. Each wire dipole would bc about 10 meters end-to end. The electronics are quite simple: a programmable low-frequency receiver (one for each dipole), a command receiver and telemetry transmitter, a low-speed CPU for control, and a power system based on a small solar-cell array and rechargeable batteries. Thea rray of packages would operate together as n aperture-synthesis, radio-interferometer array with 100 to 200 simultaneous baselines having lengths between a few km and about 100 km, Digital data would bc transmitted directly from all of the packages toa single ground antenna at 33 GHz. After reception on Earth, the data from all package pairs would be cros s-correlated and Fourier transformed on a parallel computer to produce images.

Deployment of the packages would bc via hard (uncontrolled) landings. Each package would be spin-stabilized during lunar transfer with a small solid-fuel motor slowing the package to ensure a landing impact of no more than 3000 g. This approach is very similar to that developed for the Ranger seismograph capsules and the Japanese Lunar-A penetrator. Each capsule is self-righting after landing, allowing dipole and solar-array deployment and pointing of the telemetry antenna at Earth.

The preferred launch vehicle for this mission is the Ariane S, which would allow deployment of 20 separate packages on the Moon. A Russian launch vehicle could also bc used, which might be a less expensive option, A Delta II would allow only five surface packages to be deployed, far fewer than needed for an adequate range of baselines. The numbers arc based on an estimate of 135 kg for each package, including retro motor, spin motors, payload separation mechanism, inertia arms, pilot beacon, and lander capsule with impact limiter, If deployment by means of a lunar rover were possible (as part of some other, larger lunar mission) the individual ALFA packages would be only 20 kg each or a total deployed mass of 400 kg for 20 packages. We are also investigating deployment of the array at one of the Earth-Moon Lagrange points to avoid the cost of surviving the lunar landing. This could allow a smaller and less expensive launch vehicle 10 bc used. This work is continuing, but currently it appears that lunar hard landers arc the most promising near-term deployment option.

Technology Needs

Much of the technology required for this mission is off-the-shelf. The low-frequency receivers are based on consumer-oriented portable short.wave receivers, and the digital sampling is done with commercial audio CD A/D chips. The control computers can use relatively slow CPUs which are already space-qualified. The telemetry system is nearly identical to one designed by JPL for a lunar interior structure mission. The hard-landing deployment scheme has been studied in detail (including impact survival tests of hard-landing lunar capsules) by JPL and Loral. The major technology development required is the fabrication)) and testing of a2/3 scale version of a commercial (Thiokol) solid rocket motor and the integration of the surface packages and retro motors into complete trans-lunar vehicles. Additional technology issues involve the accuracy with which vehicles can be targeted by the upper stage of the launch vehicle (and the amount of fuel required for targeting maneuvers) and verification of the impact tolerance of the solar cells and lithium batteries.

Environmental Investigation

Measure the radio noise background on near side as a function of time.

Observing Scenarios

The array would operate in two modes: 1) "snapshot" imaging of strong, rapidly changing sources such as solar and planetary radio bursts and the scintillation of strong background sources, and 2) lunar--rotation aperture-synthesis observations in which data taken over one or more lunar days arc combined for maximum sensitivity, high-dynamic-range imaging. In both cases a large number of individual array elements arc needed. Snapshot imaging is possible only if the number of simultaneous baselines is sufficient to provide good instantaneous coverage of the aperture or (u, v) plane, and full usc of rotation aperture synthesis depends on the use of self-calibration algorithms to correct for errors caused by the instruments or by propagation c.fleets. The power of self-calibration is a strong function of the number of antennas in the array.

Extensions

Increase the number of elements and the extent of the array. Place an array on the lunar far side where the radio noise from Earth is eliminated.

Ultraviolet Astronomy

By the start of the 21st century, astronomers will have had over a decade of observations from the HST and several years of observations from tbc current phase of very large telescope construction. It is thus surprising that rather modest aperture (0.5 to 1.0m) lunar based UV telescopes will be capable of making significant scientific contributions.[4] But because of the richness of the celestial field this is indeed the case, and in this brief review two possible instruments are identified.

Scientific Objectives

Two separate, stand alone, instruments have been suggested for tbc initial emplacement: a transit telescope with a fixed declination and a conventionally pointed telescope. The prime objective of the transit telescope would be a deep UV survey. This survey, although somewhat limited in sky coverage, would give invaluable statistical descriptions of, for example, the morphology of distant galaxies, or regions of recent star formation identified from the presence of hot, young, UV bright stars. Studies of the changes in variable objects such as active galactic nuclei or chromospherically active stars on time scales of one month, (the repetition period of the survey), could also be conducted. A most interesting avenue of study has been identified for the pointed telescope: stellar seismology using precision photometry. Precision photometry has become a relatively routine procedure for g,round-based, automatically operated telescopes in the visible region. Aside from the ability to observe in the UV, which is intrinsically more variable than the visible, these observations would benefit from the long uninterrupted observation periods (up to two weeks) which are possible from the lunar surface but not from low Earth orbit. These observations would provide insight into seismic vibration of stars, convectively driven oscillations, and the presence of star spots. On longer time scales, they would provide data on magnetic cycles of other stars analogous to tbc sunspot cycle of our own star.

Instrument and Mission

A disadvantage of the transit telescope is the fixed integration time set by the length of time it takes the target to cross the field of view (10, OOOS), This drives the design to large apertures. An equatorially mounted telescope overcomes this problem at the expense of introducing more complicated mechanisms which must survive and operate in the lunar environment. Design studies have not been completed for such an instrument but clearly it could be made more compact and lighter Power and data requirements would be similar to the transit telescope. The cost would clearly be a function of aperture size, although not necessarily a strong one, since the command and data handling and power systems are not related to aperture. Perhaps the main advantage is that this type of telescope lends itself most readily to incorporation into an interferometer array.

Technology Needs

A basic difficulty facing both these instruments is the provision of power, especially during the lunar night. If RTGs are not available on the lunar surface, the instruments may be restricted to operating only during the lunar day. They would then be placed into hibernation during the lunar night where they would require only minimal power (10-15 W) to keep the electronics alive. Daylight operation only is a significant rc.strict ion. A second problem affecting the transit telescope is the development of Iayc-area curved detector arrays. A second problem affecting the pointed telescope is developing mechanisms which will operate in the lunar environment with its thermal extremes and abundance of dust, both electrically charged and uncharged. In this respect it is important to note that compensating for the slow lunar rotation places these mechanisms in an awkward regime where it is difficult to generate smooth, slow motion. This area is a prime candidate for technical innovation.

Environmental Investigations

Understand the diurnal thermal cycle and the effects from the lunar dust (for mechanisms and scattering).

Observing Scenarios

The transit telescope has a 1m aperture, which is close to the lower limit for scientific usefulness, a 1.4° field of view and is operated at a fixed declination which limits sky coverage to a few per cent. The transit telescope, by virtue of its design, has a fixed pointing direction which views a swath of the sky as the Moon rotates about its axis. In order to maximize the exposure time needed for a deep survey, the telescope operates by clocking its CCD detector at a rate which matches the motion of the image of the sky across the detector (0.5 arcsec pcr see). In this configuration the. track of a star across the field of view is slightly curved; the degree of curvature being a function of the telescope's declination. Consequently, the CCD must be custom designed so that the pixel rows arc not rectilinear but are curved to match the track of the target. This scheme limits the telescope to a single declination if cross row image smear, which negates tbc advantage of synchronizing the star motion with the detector clocking, is to be avoided.

Extensions

Capabilities can be increased by more sophisticated pointing schemes, a larger primary, or extension to an interferometric array.

Infrared Astronomy

Infrared astronomy from space is currently still in its infancy. Several important space infrared observatories will soon be launched or are planned for operation in the first few years of the 21st century and will make major contributions to the science. These currently planned observatories, all of modest size, less than 85 cm diameter, with useful lifetimes of two or three years at the most, will leave many known important questions unanswered and will certainly make discoveries demanding follow up with additional space infrared telescopes. The limited capability of the planned spare infrared observatories means that very effective and useful observatories for the early 21st century need not be very large or expensive. Long lived, one meter class or smaller infrared observatories can make major contributions for moderate cost.

The vacuum of the Moon provides the needed environment for sensitive infrared observations while the solidity of the lunar surface and its proximity to Earth eliminates the need for some of the structures and systems needed for free orbiting observatories. Space infrared astronomy could take advantage of the stability of the lunar surface for operation of large interferometric arrays and larger filled-aperture telescopes.

A simple, low-mass, one-meter class, near-infrared lunar observatory, suitable for emplacement on the Moon in the next phase of lunar utilization, is described below.

Scientific Objectives

Requirements of low cost, low mass and remote, non-serviceable operation for the next generation of lunar instrumentation drive the design of an infrared observatory to the simplest kinds of usable instrumentation. A useful and important observational program that can be carried out with this kind of "suitcase science" includes deep, very wide area surveys at wavelengths from 1 to 10 microns. This wavelength range is easily accessible from the Moon with a low mass observatory, and there are no planned space observatories with the capability to survey more than a few hundred square degrees of sky to a significant depth over this band.

Very wide area surveys can be used to attack a wide variety of problems. All-sky surveys which address new wavelength regions or previously unachieved sensitivities or higher spatial resolutions have always been priceless sources of scientific data. The very low sky background of a lunar observatory and the high spatial resolution attainable with a 1 meter diameter telescope with no atmospheric distortion would allow a significant improvement in sensitivity over planned Earth based surveys from 1 to 2.5 microns. The large amount of observing time available to a long-life facility would allow surveys to cover much more sky at high sensitivity than will have been possible with precursor space IR observatories. The unbiased nature of all-sky surveys is a powerful aid in the statistical interpretation of results, and the inclusion of very large areas allows detection of rare phenomena. All-sky surveys are an archival snapshot of the universe which becomes an essential data point in the investigation of time varying phenomena such as proper motions of stars, detection of Kuiper belt objects, motions of interstellar clouds and stellar dust shells, variability of stars, and search for supernovae, to name a few.

Some specific goals of a near infrared, wide area survey would be:

- Study of low-mass stars and, possibly, brown dwarfs.
- Study of newly formed and forming stars.
- Search for and potential measurement of "dark matter" in galaxies and clusters of galaxies.
- Study the birth and evolution of normal galaxies.
- Understand the role of ultraluminous and hyperluminous galaxies in the early evolution of galaxies.
- Measure the spatial correlation of high redshift galaxies to study large scale structure in the universe.

Many more problems could be attacked as well. To be sure, the currently planned space infrared observatories will address many of these problems and will make great strides toward their solution. But, a deep all-sky survey will allow follow up work for more complete verification of results and can approach some problems, such as the mass and spatial distribution properties of low mass objects in the Galaxy and detection of very large scale structures in the universe, with much greater thoroughness than the currently planned restricted area surveys.

All observations from a survey instrument such as this might not necessarily be confined to wide area surveys. Smaller surveys to greater depth than the main survey might be performed, and maximum sensitivity observations of individual objects could be done as well.

Instrument and Mission

A near infrared sky survey observatory operating from the Moon will need to provide a pointing system to direct the telescope to the desired locations on the sky, cooling for the detectors and the telescope and electronic systems for data collection and transmission to Earth. In addition, the observatory must generate its power and control its temperature.

The pointing system can take advantage of the slow rotation rate of the Moon, 0.5 arcsecond per second, by using a transit type mounting which only provides for large motions along the meridian. If a northern and southern pair of telescopes is used to perform a full sky survey the range of motion needs to be a bit over 90 degrees. The cross motion to compensate for lunar rotation can be provided by either an internal scan mirror or a tangent arm to move the whole telescope over a range of 5 arcminutes or so to accommodate exposure times up to 500 seconds. Current infrared detector readout technology does not allow shifting of the accumulating image electronically for motion compensation, as do optical CCD detectors. A suitable, space-qualified, cryogenic scan mirror mechanism is currently being flown on the European ISO telescope. Leveling and azimuth adjustments will be needed to operate once to align the telescope mount with the lunar rotation axis to an accuracy of about an arcminute. The range of fine leveling and azimuth motion can probably be less than 10 degrees.

An operating wavelength range of 1 to 10 microns is chosen because efficient sky-background-limited operation on the Moon can be attained with a telescope temperature of 70K and detector temperatures as high as 30K. These temperatures can be reached with currently available. cryogenic coolers of modest mass and power requirements or by passive radiant cooling during the lunar night.

The focal plane would consist of InSb arrays for detection of wavelengths between 1 and 6 microns and quantum well arrays for 6 to 10 microns. These detectors are selected for their high performance at temperatures around 30K A focal plane format at least as large as 1024x1 024 for InSb and 5121, 512 for the quantum well is desirable. InSb is a well developed technology and a mode.s[increase in available array size from 512x5 1 2 to 1024x 1024 would allow construction of a focal plane. Quantum well detectors are under development with existing test detector arrays. The currently available 6 to 1 0 micron detectors, Si:As and HgCdTe, have too large a dark current and require cooling 10 SK.

Diffraction limited performance at 2.5 microns should be attainable for early 1 meter class telescopes on the Moon. Lambda/diameter sized pixels, which provide a reasonable sampling of a diffraction limited image, are obtained with a final f/ number of 16 for 40 micron pixel spacing. This speed is comfortably accommodated with a standard cassegrain telescope which locates the focal plane conveniently for cooling and bathing. A 1024x1O24 format array of lambda/D pixels on a 1 meter tc.lc.scope provide.s an 8.8 arcminute square field. As discussed later under Observing Scenarios lower spatial resolution over a larger field of view may be desirable for large-scale surveys.

Read out ofa 1024x1024 array every 100 seconds and digitization to 16 bits produces an uncompressed average data rate of about 170 kbps. Inclusion of a 512x51? long wavelength array read out every 50 seconds increases the data rate to 250 kbps. Further inclusion of observatory housekeeping data and application of a modest data compression should keep the average data rate requirement below 250 kbps for a two array observatory. A 0.25W X-band transmitter with a 0.5 meter diameter antenna will direct 2Mbps into a 10 meter antenna on Earth requiring 3 hours of down link time per day and 2.2 Gbit storage pcr day of data. Exposure times longer than 100 seconds will give proportionately lower data rate and storage requirements.

Observations in several different colors are needed to undertake a useful analysis of astrophysical measurements. Up to 8 broad photometric bands are useful from 1 to 10 microns and several narrow bands would isolate important known emission and absorption features. The selected bands can be isolated by beam splitters and fixed filters over whole arrays, fixed filters over parts of arrays or by multiple filters in a filter wheel. Larger numbers of bands can be very useful scientifically but will rapidly drive up the complexity and data rate, and thus the cost, of the observatory. A modest first observatory could certainly make very good use of as few as three or four separate band passes which could be implemented with no moving parts. The impacts on data rate and sky coverage vs. lifetime of the choice of hands and their implementation will be discussed under Observing Scenarios below.

Daytime and nighttime operating modes are feasible for a lunar infrared observatory. Daytime operation requires careful thermal design plus refrigerators and their power supply to cool the telescope and detectors to between 25 and 30K but dots not require a significant battery. Nighttime operation allows much simpler thermal design and passive radiant cooling but requires 15 days battery power. The two modes have equal requirements for communication since the Earth is essentially stationary in the lunar sky.

For daytime operation a shield against radiation from the lunar surface and good thermal design will keep the telescope outer shell at 197K in lunar daylight, A cryogenic cooler delivering 5 watts of cooling power keeps the telescope bathes and mirrors cooled to 70K for a power consumption of '200 watts and a mass of 30 kg. A sorption cooler weighing about 7 kg and consuming 30 watts cools the detectors to 25K. Such coolers already exist Some models have been space qualified and others will soon follow. A Sunshade for the telescope aperture is required to control the heat load on the cold parts of the telescope. No fixed Sunshade geometry was discovered which could provide low enough heat loading. A tracking mechanism for the sunshade will probably be required. The total power consumption of the observatory should be about 350 watts requiring a 2.5 square meter GaAs solar array which tracks the Sun during lunar daylight. Comparison with current designs for components of the SIRTF telescope and with past and current designs for lunar surface equipment indicates that (his daytime only observatory could probably be built with a mass less than S00 kg.

For nighttime operation aground radiation shield is still needed but cryogenic cooling requirements are greatly reduced, Passive radiant cooling can easily cool the telescope and can supply some of the cooling power for the detectors. A small cooler is needed for the focal plane. A small, fixed aperture shade is needed to control heat loads on the cold telescope parts The observatory can protect itself from excessive daytime heating by pointing away from the Sun toward the inside of its ground shield. Active control of radiators may be desirable to maintain roughly uniform temperatures in the warm parts of the observatory and to configure the telescope for rapid cooling during evening twilight. An estimated 85 watts of power would be required during 14 days of nighttime operation. Lightweight batteries with an energy density of 250 watt hours/kg would weigh 114 kg for this purpose. Lithium polymer batteries with energy densities in this range are under development. A 0.85 square meter solar array delivering 120 watts during daylight is needed. Without the coolers and the active sunshade, with a smaller ground shield and solar array and discounting the mass of batteries needed for daytime only operation, a nighttime only observatory would probably weigh 40 to 50 kg more than the daytime only version,

Full time operation would require both nighttime batteries and daytime coolers and sunshades but would double the available observing time. The mass for a full time observatory would probably be about 100 kg more than the daytime only version.

An RTG power supply for nighttime use is possible but politically unfavorable and more massive than batteries. A higher power RTG for daytime or full time use is also heavier than solar power plus batteries, though it may be more reliable.

Thermal design of the observatory becomes simpler with increasing absolute. lunar latitude of the observatory site. At higher latitudes the solar heating becomes more confined to onc side and the shading of the side of the observatory toward the nearest pole deepens. Taking this benefit to the extreme of locating the observatory inside a polar crater for constant shade is probably too complex for the initial return of scientific observatories to the lunar surface. Constant shading of the observatory from the Sun and Earth would require power and communication subsystems located at some distance from the telescope.

Technology Needs

Operation of a passively cooled nighttime lunar observatory requires batteries with energy densities of 200 to 300 watt hours/kg or higher. Lithium polymer batteries with this potential arc under development but would need to be made available. Quantum well array detectors are needed for operation at wavelengths to 10 µm with the cooling power available to a small observatory. Again, these. detectors are under development. Mechanisms to point the telescope while operating for many years in the lunar environment of dust and thermal extremes arc. needed as well as methods for maintaining high cleanliness of optics, thermal control surfaces anti, potentially the solar array.

Environmental Investigations

Understand the effects of lunar dust and diurnal thermal cycling.

Observing Scenarios

Awide area survey with a transit telescope requires a simple and constant observing scenario. The telescope's line of sight would be stepped along the meridian with the image at the detector stabilized against the lunar rotation rate during the integration portion of each step. The step size would be between 1/5 and 1/2 of the field of view as dictated by integration time restrictions and the desire to subsample by overlapping integrations. The ground based Two Micron All Sky Survey (2MASS), currently under development, has demonstrated the utility of this survey method. Sun avoidance constraints (>90 degrees from the Strn in the case of a nighttime only observatory) would prevent viewing of the whole sky o-c each lunar day. As the Earth moved around the Sun the sky outside the Sun avoidance constraint would eventually include all of the celestial sphere, and the full survey would be pieced together from a pattern of meridian scans over the course of several yeats. Observations at night will have inherently higher sensitivity than daytime ones since lines of sight away from the Sun have lower background brightness because they look through cooler, lowel-density dust within the Solar System.

As discussed above, thermal control requirements will probably make it desirable to place the observatory at a moderately high lunar latitude, perhaps 45 degrees from the lunar equator. Higher absolute latitude also increases the average area of sky instantaneously visible outside the solar avoidance constraint in this case two observatories, onc at 45 degrees north and one at 45 degrees south, would be required for a complete sky survey. A location near the lunar limb, as viewed from Earth, is also desirable, keeping the Earth as far from the local meridian as possible while still allowing direct communication, 10 reduce scattered light in the telescope. Alternately, if a nighttime only observatory can be designed with satisfactory daytime thermal safety margin with the Sun at zenith, it should be possible to get very c1osc to a full sky survey with a single telescope at O degrees latitude near + or - 90 degree longitude in twice the time needed for two telescopes.

The ambition of the survey undertaken by an initial lunar observatory will be dictated by the chosen spatial resolution, number of photometric bands covered, the available data rate rind the lifetime. An 8.8 arcminute square field of view covers 6.55e to 6 steradians, requiring about 2,000,000 fields to cover the full sky. A total integration time of 100 seconds pcr point on the sly with 90 percent efficiency would require about 2.1 E+8 seconds (6.8 years) to cover the full sky and would produce a sensitivity at 2.2 and 3.5 microns of about 4 micro Janskys (uJy), 10 sigma, about 150 times the expected sensitivity at 2.? microns of the planned 2MASS ground based survey, A practical survey strategy would divide the total integration time into ? to 5 separate pointings, as discussed above, and would make measurements in 2 or more bands. Assuming double coverage of the sky, two 50 second points pcr sky position, the two array focal plane discussed above would require 6 8 years at an average data rate of about 500 kilobits pcr second to complete a 2 band all-sky survey. If operation of the telescope were restricted to only half the time (night or day) the clock time for this survey would be 13.6 years. Contemporaneous operations of northern and southern telescopes would halve this time.

A sensible apportionment of resources would be to increase the field of view to 12.4 arcminutes square (1.4 lambda/D pixels), assume that either 500 kbps will be available or that on-board processing can be used to halve the data rate and plan a 2-band survey over 6.8 years of half-time operation for a single observatory. This would reduce the sensitivity to 6 uJy at 2.2 um still 100 times the 2MASS sensitivity. Reduction of coverage to half the sky allows a 4-band survey in the same time and would remain very useful scientifically. Usc of northern and southern telescopes would cut the time in half or allow for a 4-band survey of the full sky in 6.8 years, Other allocations could be made to tailor the great total scientific capability of this observatory to important astronomical question so its time.

The survey scan pattern could be interrupted for short periods to observe targets out of normal order as the target crossed the meridian. This ability will allow some number of observations of targets of opportunity or higher sensitivity observations. It will be important to retain the capability to integrate up to 500 seconds for high sensitivity observations. 'i'his reaches sensitivities near the confusion limit at 3.5 microns.

Extensions

Many logical and useful extensions of a simple initial lunar infrared observatory program are possible. Larger diameter telescopes would immediately make higher spatial resolution investigations possible. More power and mass capability for coolers or human or telerobotic servicing of cryogens would make long-term Operation of longer wavelength detectors possible. More sophisticated 2-axis pointing capability would allow observations off of the meridian which improve the flexibility to carry out diverse observation programs. The addition of spectrometers, even to a second generation of simple telescopes, would greatly increase the capability of the lunar observatory. Telescopes could be placed in polar craters with remoted power and communication for continuous passive cooling.

Development and operation of an interferometric array especially for longer wavelengths to 60 or 100 um, would be a natural step in the development of instrumentation to search for extraterrestrial planets. It is expected that operation of large interferometer arrays at infrared wavelengths on the lunar surface will be vastly less complicated and technically challenging than the operation of such arrays in orbit. The extension of infrared astronomical capability on the Moon to interferometer arrays may be a distinct breakpoint where a human or telerobotic presence on the Moon becomes desirable and appropriate. Installation of arrays of telescopes and their associated optical delay lines is an exacting task and may best be accomplished by human or robotic means rather than by autonomous deployment.

Optical Interferometry

Scientific Objectives

The Moon is an especially attractive location for optical interferometry, because the lunar surface provides a stable observing platform where the images are free of atmospheric distortions. By "optical" wc mean the broad spectral window from the ultraviolet to the infrared where imaging arrays are available as the detectors.

There arc many applications in astrophysics and planetary science where major breakthroughs would result from interferometric imaging with very high resolution, say in the range 1 to 0.1 milliarcsecond. Two outstanding examples would be the formation of planetary systems, where images of the thermal emission from protoplanetary disks around young stellar objects could illustrate, for the first time, the process of planet formation; and quasars and active galactic nuclei, where images could show the structure of the central engines that power these beasts.

Interferometric imaging would require the emplacement of dozens of telescopes. An intermediate step towards an imaging interferometer would be an astrometric interferometer, where three telescopes would suffice. With an astrometric precision in the 1 to 0.1 microarcsecond, a variety of fundamental questions in astrophysics and planetary science could be addressed, For example, an optical interferometer could search hundreds of nearby stars for evidence of low-mass companions. This could address issues such as the role of binaries in star formation (more than half the stars end up in binaries), and the puzzle of why the frequency of companions appears to drop off precipitously just at the substellar dividing line (there are no confirmed brown-dwarf companions to stars). pushing to lower-mass companions, the same instrument could be used to search for planetary systems orbiting nearby stars (no other planetary system has been detected around a star like the Sun).

A logical first step towards establishing more powerful interferometers on the Moon would be the lunar emplacement of two small robotic telescopes and the demonstration that fringes could be achieved.

Instrument and Mission

A two-node, optical interferometer with telescopes about 10 cm in aperture, and a total instrument mass of about 75 kg could be placed on the lunar surface using a Med-Lite launch vehicle. Each telescope would be mounted on a mobile platform, possibly based on the Mars Pathfinder rover. The lander would provide power, computing and telecommunications services and would carry a beam combiner box, including the delay lines, combiner optics and metrology system for the interferometer. The telescope rovers would be tethered to the lander which would provide power and command and data handling to the telescope systems via a tether that also houses the fiber optic cables carrying the star light from the telescopes to the beam combiner.

An attractive landing site is at the lunar south pole, where solar i Illumination may be year-round or nearly year-round. The Son, viewed from the landing site, would travel around the horizon once per month, while the Earth would bob up and down, above and below the same location on the horizon, staying within communication line-of-sight for more than two weeks at a time. This property of the landing site may make it a good site to perform radio science experiments as well. Another desirable aspect of a polar site is that the rotation of the Moon would swing the interferometer baseline around in the uv-plane, allowing for synthetic aperture imaging without requiring rover movement.

The telescopes would be mounted to allow for coarse and vernier elevation and azimuth control, providing hemispherical coverage, arid allowing for very long observations.

The scientific return from such a mass limited system would be very limited; the primary mission objective is to form fringes as part of a few simple observations, as mentioned above.

Extensions

To address the astrometric scientific objectives, three somewhat larger telescopes, e.g., of the 1-meter class, over baselines of 1 or 2 km, would be employed. The evolution to an imaging interferometer would involve the emplacement of one or two dozen more telescope units over a somewhat expanded area.

Lunar Kilometric Imaging

Scientific objectives

Magnetospheric Imaging

An imaging array on the lunar surface would allow remote sensing of kilometric radiation from magnetospheric structures and would image the location of the radiation emanating from the magnetosphere. An image made of this radiation from the lunar surface from a 100-km instrument allows a few-degree resolution of a structure which can extend over the whole sky as seen from the Moon. To study auroral kilometric radiation (AKR), the most powerful (but highly variable) of Earth's naturally occurring kilometric radiation, it would be necessary to view as many different frequencies from 20 to 200 kHz as possible (~20) over short time intervals (~1 sec) throughout the hours-long period of the substorm activity. Observations need not be continuous, but should sample the AKR at regular times throughout a substorm.

The AKR is produced in one location close to the Earth and varies nearly the same in strength over a wide range of frequencies. If possible, imaging at different frequencies over times short compared to light travel times would have the advantage that light-time propagation effects along the magnetotail could be used in addition to other parameter changes to study the intervening structures.

Other types of kilometric magnetospheric radiation which could be imaged from the lunar surface include radiation from the 2fp line, which occurs naturally near the bow shock of the Earth, and NTC (non-thermal continuum) radiation which is present at a much lower level in the magnetosheath region of the magnetosphere.

Solar Radio Burst Imaging

The different types of solar radio bursts observed in the kilometric range and formed at the local heliospheric plasma frequency (or its harmonics) would benefit from imaging. The strongest radiations at Earth are from type III radio bursts caused by high-energy electrons which move through space and occasionally engulf the Earth. These take anywhere from 20 minutes to several hours to travel from Sun to Earth.

Of perhaps more interest for solar-terrestrial studies are type II radio bursts, which can take several days to travel the distance from Sun to Earth and are associated with shock waves propagating in the interplanetary medium. This latter radiation has the potential of being used to forecast the Earth-arrival of the fastest mass ejections (which accompany them) and are known to cause large substorms on Earth.

Instrument and Mission

In essential details, the description of the Astrophysical Low-Frequency Array is applicable.

Observing Scenario

Observations need not be continuous but should sample the AKR at regular times throughout the. substorm.

THE ECONOMICS OF REUSABILITY

The economic verdict on whether reusability of remote-sensing assets is of significance for lunar planning awaits designs with enough detail to be costed, and that level of information is not presented in this exploratory paper.

Pure Strategy

Nevertheless, it is useful to consider what principles might come into play that could lead one to expect savings. A schematic of the concept is shown in Figures 1 and 2.

The analysis behind these figures is exceedingly simplistic in its assumptions, but it exposes key dependencies and gives a rough effort of what must be achieved in order to make reusability effective for a series of lunar missions.

Figures 1 and 2 give qualitative pictures of what one might call the "pure strategy" for lunar-observatory reusability ("mixed" and "focused" strategies will be introduced later).

The assumptions inherent in these pictures are:

(1) N is treated as a continuous quantity rather than assuming discrete (integer) values as it does in reality.

(2) The cost, F, of free-flyer missions is the same for each mission in the series. This need not be the case, since free flyers could also utilize a reusability strategy (robotically implemented or through the aid of astronauts). However, there are certain scenarios where the Moon does appear to have an advantage over free flyers. For example, multiple spacecraft formations (as in interferometric arrays) tend to disperse over time due to differential solar radiation pressure on the individual vehicles. Another example is given by that uniquely two-dimensional creature, the lunar (or planetary) rover, whose three-dimensional analog is, in many ways, more complex. Also, the repetitive lunar-station to Earth - station link geometry makes the reuse of communications equipment attractive. Finally, repetitive Sun and lunar-station geometry facilitates planning for the use of (predecessor flight-system) shade patterns for (successor) thermal control.

(3) The cost, F+H, of a series of independent lunar observatories, with the. same scientific scope as their free-flyer counterparts, is the same for each mission in the series and, also, is H dollars per mission more than a free-flyer, the lunar handicap (gravity well, etc.).

(4) In the steady state, reusability could drive the cost per mission to as low as R > 0 dollars below free flyers.

(5) There is a penalty of P dollars per mission in order to equip the. system for reusability.

(6) The cost per reusable mission decreases by a constant fraction, k, of the span between top cost (F+H+P) and bottom cost (F-R) for a reusable observatory.

(7) Monetary inflation is 0 over the time span considered (or countered by technology increase).

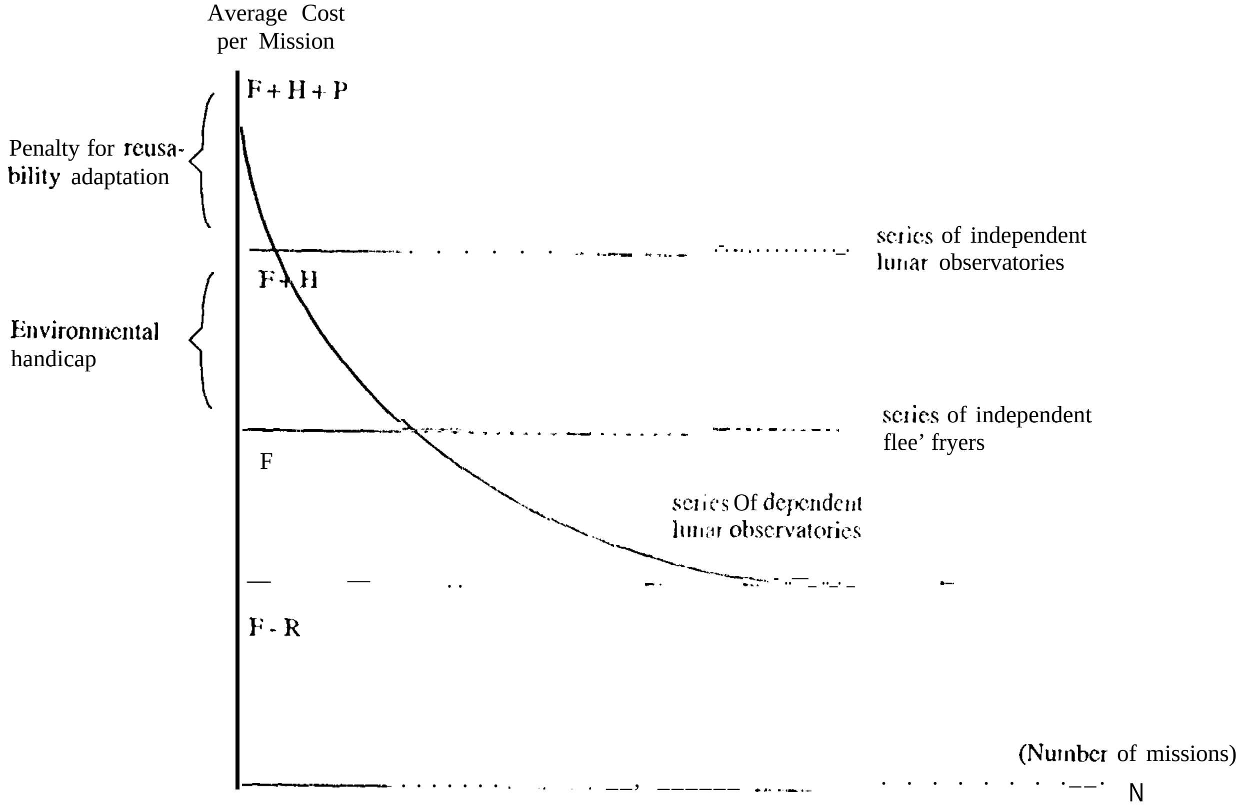

Figure 1. If assets from previous lunar observatories can be (partially) reused by subsequent observatories, the cost per investigation will decrease. The curves are idealized in many ways including, for convenience, representation of the reusable case by a smooth curve rather than a chain of step functions. The horizontal asymptote accounts for the facts that there are always costs associated with a mission and that emplaced assets eventually break down or become obsolete.

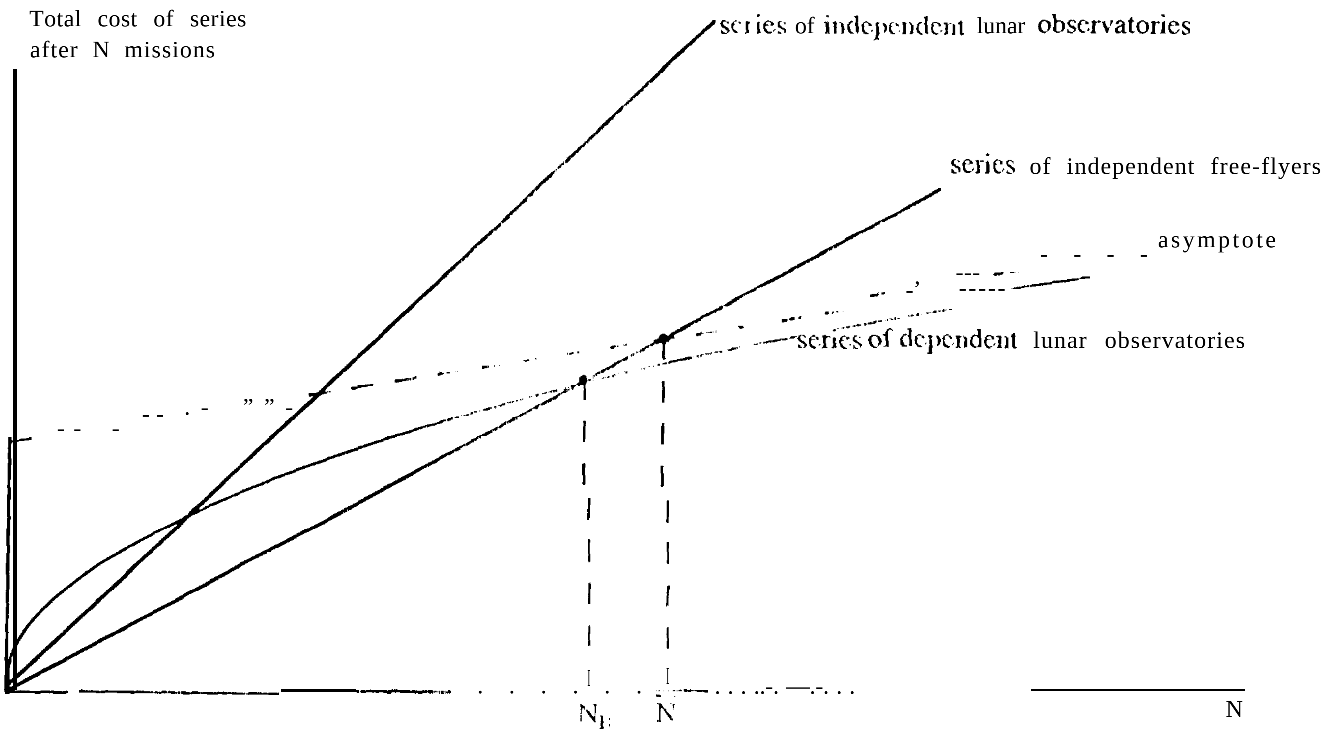

Figure 2. Integration of the curves of Figure 1, The point N_E is the 'break-even' number; if N_E or more partially reusable missions are flown, the total cost for the series will be less than for a similar series of independent free flyers. See equation (8) for N.

With C' denoting the cost per mission and subscripts R,F,I denoting reusable lunar mission, free flyers, and independent lunar missions, respectively, then,

$$C'_R(N) = (H+P+R)\exp(-k(N-1)) + (F-R) \qquad (1)$$

$$C'_F(N) = F \qquad (2)$$

$$C'_I(N) = F + H \qquad (3)$$

describe Figure 1. Integration of (1) through (3) provides the analytical description of Figure 2 (with C, no prime, denoting the cumulative cost for the series).

$$C_R(N) = [(H+P+R)/k](1-\exp(-k(N-1))) + (F-R)(N-1) + F+H+P \qquad (4)$$

$$C_F(N) = FN \qquad (5)$$

$$C_I(N) = (F+H)N \qquad (6)$$

The break-even point for lunar investment occurs when

$$C_F(N) = C_R(N). \qquad (7)$$

A figure of merit (an approximate version of equation (7)) is obtained by solving for the intersection $\bar{N}$ of $C_I(N)$ and the straight-line asymptote to $C_R(N)$:

$$\bar{N} = (H+P+R)(1+1/k)/R. \qquad (8)$$

The smaller that $\bar{N}$ is, the better. Some tabular results give a feel for the quantities involved. The cost unit is taken to be $F = 1$.

Parametric Case	H	P	R	k	N_B	$\bar{N}$
1	0.25	0.25	0.5	0.1	19	22
2	0.10	0.10	0.5	0.1	10	5
3	0.10	0.10	0,5	0.2	5	8

Table 1. Examples of break-even points N_B in terms of model parameters. For, $\bar{N}$, the figure of merit, see equation (8)

It seems reasonable, from programmatic and engineering institutions, to require $N_B \leq 5$. Thus, for one launch per year, the break-even point, N_B, would be reached in five years. Of course, there are many tradeoffs to be conducted but this constraint on N and inspection of Table 1 shows that cases 2 and 3 exemplify viable parametric values. Of course, no evidence has been presented to show that such parametric values are attainable.

Mixed Strategy

Although the kinds of numbers (Table 1) that seem to be needed in order to pursue a pure strategy and achieve economies of reusability in a reasonable amount of time are not "scary," it cannot be said, without much more design and analysis, whether the endeavor would succeed or not. Hence, one looks for ways to ameliorate the difficulties.

One obvious strategy is to look for parameters so that the (NASA) cost is partially offset. Commercial prospects with regard to the Moon have been raised in the past five years or so, and it is not unreasonable to contemplate using some commercially emplaced assets to lower the cost of missions. In this case, the lunar environmental handicap, H, would be decreased and might even go negative.

No numerical studies are needed to illustrate the point that the mixture of commercial asset sharing and reusability could be even more economically attractive than a pure strategy.

Focused Strategy

If one focuses on certain kinds of scientific missions which lend themselves in a natural way to being augmented, then the penalty, P, for reusability adaptation could be expected to be quite small. For example, adding on to an optical or radio interferometric array would seem to be an easier thing to do than to stringing together a diverse series of investigations.

SURVIVAL ON THE MOON

In order for a reusable strategy to be viable, assets from earlier emplacements must survive the traumas inflicted by the lunar environment.

As a prelude to examining the imprint of the lunar environment on engineering systems, some aspects of that environment will be summarized. For an in-depth view, the book of Heiken, Vaniman, and French is recommended.[6]

Lunar Environment

The lunar environment challenges, with respect to situation of remote-sensing facilities include: temperature; radiation; dust; micrometeorites; stability.

Temperature

Temperatures have been measured from Earth and *in situ* by surface missions. The range of temperatures on the lunar equator is from about 90K (night) to 385K (day). The thermal cycling of approximately 300K can be significantly reduced by moving from the equator to higher latitudes. In polar areas, the average temperature drops 30K or so, and the range contracts markedly: to perhaps a 20K variation. Sheltered polar craters can be very cold (c.40K) with almost no fluctuation. (Of course, power problems need to be solved in the absence of Sunlight.)

Radiation

The Moon is outside of the shielding effect of the Earth's magnetic field and, thus, is exposed to much of the same radiation environment as a deep space probe. Solar wind particles, high-energy galactic cosmic rays, and rare but intense solar flares are the primary types of radiation to be encountered.

The degradation of electronic components is the principal consequence of radiation for robotic missions to the Moon

Dust

Dust has been created on the Moon through the continual bombardment of the surface by micrometeorites. It can contaminate optical and heat-sensitive surfaces and adversely affect the movement of mechanisms.

Considerable data has been taken, including Apollo dust experiments. (Also, the landing of Apollo 12 within 160 m of The Surveyor 3 spacecraft resulted in the deposit of dust on the optical mirror of the robotic vehicle.)

Micrometeorites

Micrometeorites pose a concern for pitting of exposed optical surfaces since they arrive at velocities of about 15 km/sec. Over a year's time, several hundred craters in the 1 to 10 micron range would be created on exposed optical surfaces.' (For reference, one thousand 10 micron craters would occupy 1 part in 10' for a square meter.)

Stability

Although the. Moon is much less seismically active than the Earth', by many orders of magnitude, lunar bedrock is not readily available for observatory sites and shattered regolith is the lunar material to be expected.

Apollo measurements show that seismic motions result in shifts of only a few tens of nanometers. Tidal deflections of about 1mm can result over a 5 km baseline due to tidal libations.'

Response of Engineering Systems to the Lunar Environment

Anecdotal coverage of this area is presented here because the complex lunar environment played against the enormous spectrum of possible systems precludes anything of a comprehensive nature in the space available. The intent is just to convey a feeling for the. magnitude, of the. problems.

Surveyor 3

The Surveyor 3 spacecraft was soft landed on the Moon on April 20, 1967 in a small crater in the Ocean of Storms. All of the subsystems operated successfully throughout the lunar day. The television camera took more than 6000 photographs o! (It lunar terrain. The spacecraft failed to respond 10 attempts to revive it during the second lunar day. (Survival of Surveyors through lunar night was not a design requirement.)

In November 1969, two-awl-one-half years later, the Apollo 12 lunar module touched down near the Surveyor 3 site, and the astronauts retrieved the television camera and some other parts after the robotic craft had soaked in the lunar environment for some 32 day/night cycles.

The television camera was delivered to the Hughes Aircraft Company (builders of the device) facility in Culver City, California, and there, under the technical direction of JPL underwent a test and evaluation program.[8]

Before looking at some aspects of this report, it is worth noting that it only tells a small part of the reliability story: the time period is only half of the five years discussed in reusability scenarios; the technology involved is now quite old (e.g., a vidicon and electronic circuits that were not as densely packed--and, thus, radiation susceptible--as today's); flight systems consist of more than cameras.

Nevertheless, the experience has two virtues: (1) it is lunar based and not analytical or simulated, and (2) the device is a relatively complex piece of engineering.

Tests included:

- Optical surfaces
- Thermal control surfaces
- Mechanical devices
- Electrical components (resistors, capacitors, diodes, transistors, potentiometers)
- Magnetic components
- Vidicon tube and its elements
- organic materials
- Adhesives, lubricants, and seals,

As a result of the testing program the conclusion was (page 1-9): "...actually, the effect of the lunar environment on the specific anomalies uncovered in the course of the program was relatively minor"

To give a sense of the anomaly analysis. Table 1-3 of reference 8 is reproduced, in part, as Table 2.

Notes on More Modern Systems

Clearly, as indicated previously, there are many engineering systems to be considered and many environmental effects to be analyzed. Continuing the approach of this paper, only notes will be provided to indicate the nature of problems and possible solutions. Three areas have been selected for this treatment: electronic parts, packaging, and mechanisms.

Electronic parts

The principal issues affecting electronic parts reliability arise from radiation and temperature. The Cassini mission to Saturn is designed to tolerate a total ionizing dose of 100 krad, and this figure may be representative of some lunar-observatory scenarios

ANOMALY	Effect of Lunar Environment	
	Primary Case	Secondary or Contributory Case
Surveyor 3 Mission Anomalies		
Inoperative filter wheel potentiometer	No	No
Occasional difficulties with stepping in azimuth	No	No
Veiling glare	Yes	
Effects on Optical and Exterior Surfaces		
"Mud-cracking" of external painted surfaces	No	Yes
Oust on filter glass	Yes	
Discoloration and curling of teflon skirt	Yes	
Discoloration of external painted and other surfaces	Yes	
Open Shutter and Related Failures		
(Burnt out transistor, shorted solenoid, evaporated vidicon photoconductor, and torn grid)	No	Minor, if any
Defective Electronic Components		
Cracked glass case	Yes	
Defective diodes	No	Some
Shorted tantalum capacitor	Yes	
Two burned-out obsolete components	Yes	
Suspected Cold Weld of Connector Shell to Shroud	No	Yes
Four Miscellaneous Minor Anomalies	Yes	No

Table 2. Surveyor 3 Television Camera Anomaly Classification

The temperature extremes present both an operational reliability and radiation problem. Military parts are specified over the range of -55°C to +125°C. Care should be taken to allow appropriate heat sinking at high temperature such that the junction temperatures do not exceed +150°C. Failure mech-anisns associated with high-temperature operation include threshold voltage decrease and increased leakage current in CMOS devices due to ionic contamination. Electromigration (of conductors) is also exacerbated by high temperatures. The good news is that TID (total ionizing (Ire+) response typically improves with temperature due to It, ? annealing of the trapped charges that arc induced by ionizing radiation. On the other hand, the trapped hole annealing may cause "rebound" (i.e., the interface states may become predominant) and result in a degraded threshold voltage and leakage current. This effect is highly process-dependent. Single-event latchup effects become worse at high temperatures. Single-event burnout improves with increasing temperature. Single-event gate rupture has no strong temperature dependence. Single-evenl upsets occur more frequently at high temperature for dynamic RAM, structure, but have no strong temperature dependence for latch type structures (e.g., static RAM cells, flip flops).

Low-temperature operation typically improves CMOS circuit operation in terms of speed and power, but hot carrier effects that can reduce threshold voltage become apparent at low temperatures. Bipolar transistor gains also degrade appreciably at low temperatures and arc even further exacerbated by TID and, hence, should be characterized prior 10 application.

Carrier freeze out, which occurs at low temperatures and is technology and process dependent, essentially prevents carrier recombination and, hence conduction.

In conclusion, operation at the high-temperature extremes, with the exception of the degradation effects of single-event latchups and single-event upsets for dynamic RAMs, is less of a reliability risk than operation at the low-temperature extremes. Characterization, low-temperature burn-in and radiation, are recommended for flight technologies. Temperature cycling in the course of the lunar day may improve the radiation risk but may affect mechanical and material integrity.

Packaging

"The dominant failure mechanism of typical packaging designs is low cycle fatigue of interconnects. This mechanism results from a global mismatch of the coefficient of thermal expansion (CTE) between: (1) the part and the board it is mounted on, (2) the board and the board housing. Local CTE mismatches (between solder material and metal pad on the board) also contribute to the problem.

'1 he material properties which govern the life of solder interconnects are very nonlinear As a result, cyclic exposures which involve higher peak thermal exposures are significantly more damaging than cycle exposures of the same total depth but which involve a lower hot peak temperature. Moreover, below 273K, the solder material becomes significantly stronger and thereby most likely changes the failure mode for the interconnect from a fatigue failure of the solder material to a brittle failure of either the solder material or the part-lead material. Furthermore, the actual part temperatures may be significantly higher than the external ambient temperature due to power dissipation and the internal thermal resistance. If large internal temperature rises do exist, it may be necessary to switch to high temperature solders both at the joint and possibly inside the component (configuration dependent). If temperature rises can be held to a minimum or if other thermal control techniques are utilized to lower the effective part temperature, then traditional lead/tin solder should be acceptable.

Mechanisms

Future lunar space missions will require high performance, reliable, long-life mechanical systems with moving parts; there is a concern in the space community that the current technology level in basic areas such as bearing, gears, seals and lubricants may not meet mission goals. A summary of future needs and concerns of space mechanisms are:

- There is not enough data available for mechanisms operating in space for long duration because very few systems have operated that long and none has been returned. The Earth orbiting Long Duration Exposure Facility (LDEF) experiments were exposed to a more benign environment than the lunar surface, and most of the elements were in non-operating conditions.
- There is a concern about thermal cycling for lunar landers which may experience large temperature differences (extremes); there is limited experience of temperature extremes in vacuum for long duration.
- There is a concern about contamination and survivability of mechanisms in the severe lunar environments with dust and abrasive material.
- There is a concern that existing and untested lubricants may not meet the increasingly restrictive instrument requirements in temperature tolerances, radiation resistance, and micrometeorite damage, along with long life.
- Some lubricant problems have not been solved yet such as: outgassing; drawbacks of dry lubricants; liquids: aging materials, particularly rubber and plastic,
- There is a need to develop consistent comparison of test results and to establish reliable criteria for accelerated testing of friction and wear. Solid lubricants might be more suitable for accelerated testing than liquids.
- There is a concern about dither motion over small degrees of rotation, sliding, mechanism surfaces and wear, and the selection of best material. Also the vibration and shock of landing (in addition to temperature and low gravity) cause mechanism failure by affecting lubricant distributions, tolerances and surface contacts.
- There is a concern that although test methods may be adequate to qualify flight hardware, some test facilities are not adequate for simulating the long term space environment (vacuum, temperature, low g), and dynamic testing facilities for lubricant characterization. There is a need for space qualification techniques for lunar operations and a need for chambers simulating micrometeorite bombardments.
- Mechanism technologies identified for further development are: seals and sealant (O-ring, gaskets); bearings (lubrication, contamination); lubrication of reaction-wheel bearings operating for long life; very low speed (lower than elasto hydrodynamic lubrication) rolling element bearings; motors and gear trains; magnetic or other non contacting bearing for scalable long life equipment; abrasion, radiation darkening, contamination resistant optical surfaces and solar cells; composite materials for mechanisms; light-weight, high-strength alloys such as Al-Li alloys; robotics and telerobotic servicing and unmanned exploration; direct drive systems minimizing the use of gears; reliable power-generation systems and improved battery technology; cryogenic lubricants; lubricants for high hertzian stress sliding contract; self verifying deployment mechanisms and intelligent mechanisms; precision point and control mechanisms, vibration isolation; robotics joints and grippers; connectors and disconnectors, and servomotors; adequate low speed (lower than elasto hydrodynamic lubrication]) rolling element bearing for vacuum

CONNECTIVITY

'Connectivity" is used here in a very general sense to denote any links between a predecessor and a successor flight system both on the Moon, that result in the successor mission being able to utilize, to its advantage, capabilities of the predecessor system. Another word that could be used to describe the idea is "inheritance," but "connectivity" conveys some of the nature of the challenge in linking predecessor to successor.

Connectivity has proved of great importance in NASA's astrophysics program through upgrades to the Hubble Space Telescope: past and planned for the future. However, the nature of the challenges is quite different for servicing missions by astronauts in low Earth orbit than for creating robot-to-robot connections on the Moon.

The previous economic analysis was done with the intent of showing that partially reusable systems might indeed prove attractive enough to at least stimulate some though as to what design solutions are most promising. The present section represents a step in the direction of identifying, a few such solutions.

Instrument Change-out

The canonical example of reusability for Earth-based observatories is to retain the structure and optical system of a telescope and replace the focal-plane complement with new sensors and devices as they become available. For example, the 5 m telescope at Palomar is a very different scientific instrument from the one that saw first light in late 1947.[9]

The challenges associated with this upgrading (or extending to difference sensing regimes) scheme are obvious. First, there is the sheer technical difficulty in devising flight systems designs that enable a reliable robotic change-out to be done. Second, even if one has such a design, the cost (Pin equation (1)) is likely to be high. An ameliorating factor is the fact that designers have not really explored, in a determined way, flight system architectures with these requirements.

Instrument Augmentation

The augmentation that comes most readily to mind is adding nodes to an existing interferometric array: optical infrared, or radio. The advantages are clear: more UV-plane coverage and additional photon-collecting capability. Connectivity challenges arc not trivial but design solutions do not seem inoperable.

A variant of this scheme is to add small interferometric "outrigger" telescopes to a larger, central telescope that has already been operating (the predecessor system). Such an approach has been studied for the two Keck telescopes on Mauna Kea.

Inherited Rover

Rovers are useful adjuncts to scientific investigations and, depending on their design, can be used for a variety of engineering or scientific services. . Since they are quite likely to be able to communicate easily with the predecessor mother lander, this communication could readily be extended to a successor lander.

Passive Thermal Control

More simply put, predecessor structures will produce shade that can be utilized in an appropriate manner.

Inherited Data Systems

A transmitter-reccivcl on a predecessor system could be tapped and utilized for direct communication with Earth.

Sirni lady, compute power and memory could be augmented using predecessor systems.

Inherited Power Systems

The transfer of power is more problematic than the exchange of bits, hut the temptation to reuse solar panels is a strong motivation.

SUMMARY AND CONCLUSIONS

There arc reasons to believe that situating certain types of robotic observatories on the Moon can be scientifically and economically competitive with situating them in a free flyer environment.

- Reusability of scientific and engineering systems decreases total costs for a series of missions and is facilitated by geometric constraints
  - Invariant relative geometry, including no dispersion, between predecessor and successor assets
  - Tu'o-dimensional mobility space for rovers
  - Repetitive relative configurations between lunar stations and Earth stations and between lunar stations and Sun (implications for, respectively, reuse of communications links and use of shade from predecessor flight systems)
- Survival of flight systems on the Moon, over a period of years, appears to be possible without heroic precautions
  - As evinced by previous lunar experience such as Surveyor 3
  - As indicated by other deep-space experience and analysis

However, the case is by no means established and more work would need to be done to as.sex<, with confidence, the value of the Moon as a venue for scientific remote sensing.

Areas which net-d to be examined are:

- Scientific program
  - High value science
  - Implementable with low-mass systems
  - Constituted by a series of richly reusable observatories (may rely on "focused" strategy)
- Connectivity
  - Search for new, innovative ideas which utilize the fact that the Moon is not space
  - Interact with the scientific program for the series
  - Survivability
  - Employ the best lunar-environment models
  - Identify the most life-limiting hardware issues in the lunar environment
- Cost analysis
  - Against at least one point design for a series of missions. identify sensitivities
  - Compare to the best that can be done with free flyers
- Technology
  - Identify those inventions or upgrades which would lower costs or increase scientific returns for a series of lunar observatories
  - Estimate the cost and schedule for development of such items
- Programmatics
  - Develop implications and prospects for a "mixed" strategy: government plus commercial use of the Moon
  - Consider how a lunar series of missions might relate to a NASA/Explorer line of missions

It is apparent that this examination must be done in the context of a system design for a series of missions. Careful trades between scientific choices, reusability designs, and reliability steps are necessary for making the concept work.

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